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Analytical Study of Sub Terahertz Radiation from Ultrashort Laser Pulse Propagation Streamers

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Conference Presentation

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14. ABSTRACT
A numerical calculation based on Maxwell's equations was made to examine the details of this process. The numerical calculation proceeded from Maxwell's Curl equations and included the treatment of the of the polarization current by means of a non linear oscillator model.
The oscillator is linear for small displacements but becomes non-linear for large fields where the Kerr Effect is important. The oscillator equations of motion determine a non-linear polarization current that is included as a source term in the Maxwell's equation simulation. This simulation determines the time dependant dipole moment density of the ionization charge distribution. These dipole moments can then be integrated to find the near field and radiation field components of the fields from the standard integrals. The details of these results also show a lower frequency component of the field, but it is still an optical frequency about a factor of 10 lower than the laser frequency. The results do not show the sub terahertz radiation reported in the literature. An interpretation of this is that the measured fields must be very small, coming from second order effects not included.

15. SUBJECT TERMS
Ultra-short laser ionization streamer radiation terahertz

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Analytical Study of Sub Terahertz Radiation from Ultrashort Laser Pulse Propagation Streamers

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Outline

- Ionization streamer formation and propagation synopsis
- "NSLE" propagation ionization numerical simulations
- Reported data and theory
- Analysis of the possibility of radiated fields
  and corroborating Model
- Maxwell numerical simulations
  and test case results
- Conclusion and comments

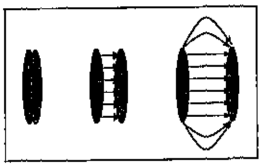
RF Radiation from Laser Filaments

- THz and sub-THz radiation from short pulse laser filaments have been reported.
- Sub-THz radiation from longitudinal plasma filament oscillations has been predicted observations reported by Tzortzakis et al (02).
  - Cheng et al (01) have proposed plasma oscillation mechanism
  - This mechanism has been challenged (Carron, 02)
  - Carron states filament can only radiate from discontinuities when filament starts and stops.
  - Traveling wave model supports Carron's results (Zimmerman, 02)
- At present there is a shortage of quantitative data and no satisfactory theory for observed sub-THz radiation

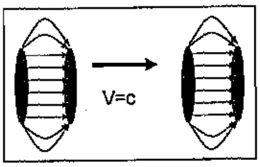
Comments on this Chart:

Among the interesting phenomena generated by these laser filaments in air is the emission of THz and sub THz electromagnetic radiation. Both near and far field measurements have been made by various investigators. Unfortunately the reported data is qualitative in nature. A model of sub THz radiation was proposed by Cheng et al in which longitudinal oscillations are excited by the laser pulse. This model has been challenged on two grounds. The first is that a traveling current pulse is not expected to radiate except at discontinuities. The second is that the electron neutral collision frequency is on the order of 10^12 sec-1 and so sub THz oscillations would be expected to be damped out. At present there does not appear to be a satisfactory model to explain the experimental results

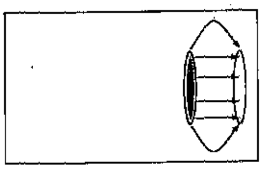
Analysis of Filament Fields



Phase 1: Initial Dipole Is Created
- "Capacitor" Is Created
  - Electrons "Pushed" Ahead by
    - Radiation Pressure
    - Ponderomotive Force
- Changing Dipole Moment Creates Radiated Field



Phase 2: Dipole Moves with Laser Pulse Leaving Plasma Trial
- Two Possibilities
  - "Capacitor" Moves with Uniform Velocity & Trailing Neutral Plasma
  - Electrons Move with Uniform Velocity & Trailing Positive Plasma
- Neither Case Creates Radiation



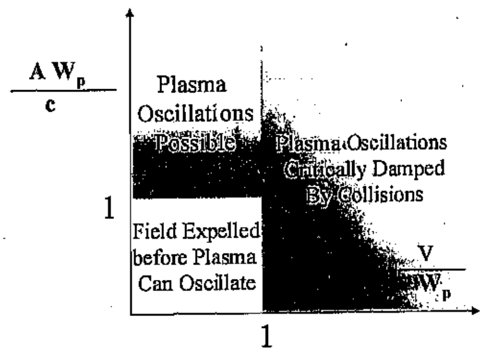
Phase 3: Dipole Decays
- Both Phase 2 Possibilities Finally Leave Neutral Plasma
- Dipole Creates Radiation as it Diminishes

Comments on this Chart:

1. Initial dipole is created, a radiated field is created since there is a 2nd time derivative of the dipole moment
2. The pulse propagates, there are only linear rates of dipole moment change so the 2nd derivative of P is zero and there is no radiated field
3. The dipole is extinguished, a radiated field is produced since there is a 2nd time derivative of the dipole moment

Diagram of Possible Ionization Streamer Oscillations

from Scaled Plasma Frequency Parameters



Wp is the plasma frequency

V is the collision frequency

a is the channel radius

Envelope Equation Approach

Maxwell's Equations

$$\vec{\nabla}\times\vec{E}=-\dot{\vec{B}};\quad \vec{\nabla}\times\vec{H}=-\dot{\vec{D}}+\vec{J}$$

Uniform Media

No Free Charge

Wave Equation

$$\left(\nabla^2-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E}=\vec{S}$$

Field Is Slowly Varying Envelope, A, of Single Frequency Sinusoidal Wave

Sources Also Slowly Varying Envelope of Single Frequency Sinusoi dal Wave

Expansion of Linear Source Term $S_L=\left(\frac{\omega_0}{c}\right)^2\sum_{j=0}^{\infty} i^j\alpha_j\omega_0^{-j}\frac{\partial^j A}{\partial t^j}$

Transformation from Real to Retarded Time

Envelope Equation

$$\left[\nabla_\perp^2+2ik_0\frac{\partial}{\partial z}-k_0\beta_2\frac{\partial^2}{\partial\tau^2}+\gamma|A|^2-\frac{\omega_p^2}{c^2}\left(1-i\frac{\nu_e}{\omega_0}\right)+i\frac{8\pi k_0\beta^{(7)}}{c}\left[|A|^2\right]^6\right]A=0$$

Kerr Term

Plasma Term

(Multi-photon) Ionization Term

Comments on this Chart:

This shows the derivation path from Maxwell's Equations to the Envelope Equation

1. With Uniform Media and no free charge, Maxwell's equations becomes the wave equation
2. Envelope approximation, expansion of linear polarization in terms of time derivatives of the envelope and transformation to retarded time gives final envelope equation

Real Time Maxwell Algorithm

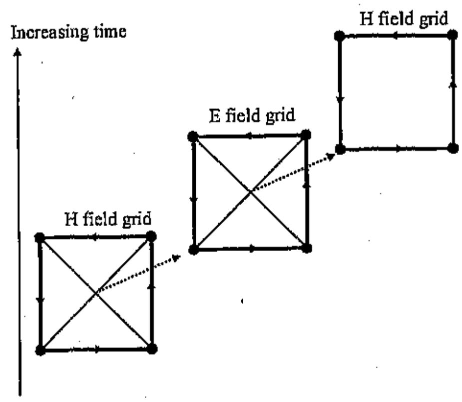
Instead of the using a wave equation the curl equations are directly solved simultaneously

$$\nabla \times E = -\dot{B}$$

$$\nabla \times H = -\dot{D} + J_t$$

The media polarization current is determined from a nonlinear oscillator model analyzed (via ODE's) in conjunction with the field time stepping

Using the Yee algorithm the E field and H field meshes are offset in space allowing centered 2nd order curl differencing for finding E or B at a new time step from H or E at the old time



Comments on this Chart:

Start with Maxwell's equations

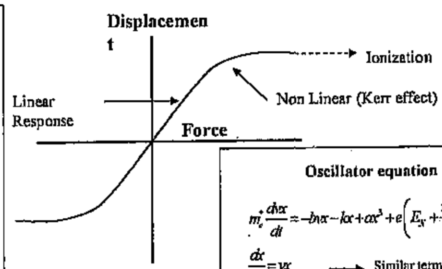
Yee Algorithm has Electric Field and Magnetic Field offset in space and time

Inclusion of Frequency Dependant Properties In The Time Domain Calculation

Non nonlinear media are included by solving a simple oscillator equation including both linear and nonlinear terms

Simultaneously carrying this solution provides a polarization current for Maxwell's Eqs.

The oscillator coefficients are determined from optical data



Oscillator equation of motion

$$m_e^* \frac{dvx}{dt} = -bvx - kx + \alpha x^3 + e\left(E_x + \frac{\eta_0}{c}\left(H_z \cdot vy - H_y \cdot vz\right)\right)$$

$$\frac{dx}{dt} = vx$$

→ Similar terms for y and z

$$\Rightarrow \frac{d\bar{v}}{dt} = -\left(\frac{S}{n_c} + v_m\right)\bar{v} + \frac{e}{m_e}\left(\bar{E} + \frac{\eta_0}{c}\bar{v}\times\bar{H}\right)$$

Polarization Current

$$J_z^{polarization}(A/m^2) \sim n_o e vz(t)$$

→ Similar terms for x and y

Maxwell Equation

$$\nabla\times H = -\partial D/\partial t + J_{TOTAL}$$

Comments on this Chart:

Solution of Fields are combined with Source term computation

Shows details of mapping between a harmonic oscillator model and the nonlinear effects

Oscillator model

1. Begins with linear part
2. Extended to non-linear (Kerr) effect
3. Finally results in ionized atom

Finite Difference Model ODE's

Electric field ODEs for the elemental cell (Include corresponding Y and Z Terms)

$$(\dot{E}_x)_i = -\left(\frac{\sigma_i}{\varepsilon_i}\right)(E_x)_i - \left(\frac{n_o e}{\varepsilon_i}\right)(v_x)_i - \left(\frac{e}{\varepsilon_i}\right)(p_x)_i$$

Dielectric/polarization model, $\dot{x}_i = (v_x)_i$ (Include corresponding Y and Z Terms)

$$(\dot{v}_x)_i = \left(\frac{e}{m_e^*}\right)(E_x)_i + \left(\frac{e}{m_e^*}\frac{\eta_o}{c}\right)\left(<H_z>_i (v_y)_i - <H_y>_i (\dot{v}_z)_i\right) - (2\gamma)(v_x)_i - (\omega_r^2)x_i + ax_i^3$$

Dielectric/polarization model, $\dot{n}_i = S_i$ (Include corresponding Y and Z Terms)

$$(p_x)_i = -\upsilon_m (p_x)_i + \left(\frac{e}{m_e}\frac{\eta_o}{c}\right)\left(<H_z>_i (p_y)_i - <H_y>_i (p_z)_i\right) + \left(\frac{e}{m_e}\right)(E_x)_i n_i$$

Ionization model

$$S(e/cm^3 - \sec) = \frac{dn_e}{dt} = n(N_2)R_{N_2}(I/I_T)^{\alpha_{N_2}} + n(O_2)R_{O_2}(I/I_T)^{\alpha_{O_2}}$$

Comments on this Chart:

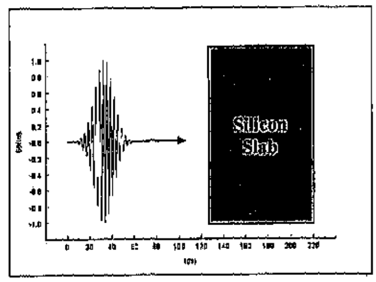
This shows how the physics equations become algebraic equations to be solved

1. The electric field depends on the linear and non-linear sources
2. Bound electrons move under the effects of the electric and magnetic fields as well as the restoring forces of the oscillator model for bound electrons
3. Free electrons move under the effects of the electric and magnetic fields.
4. The equation for the ionization is also shown

Computational Check out problem

A femtosecond pulse propagating in air impinges on a Silica slab.

This problem has been calculated to check out the Maxwell formulation and results.



The form of the incident pulse in the these code checkout calculations is taken to be:

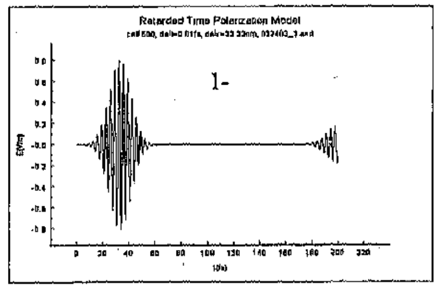
$$E(t) = E_o \exp\left(\frac{-0.5(t-\tau)^2}{\Gamma^2}\right)\sin\left(2\pi f_o (t-\tau)\right)$$

$$\Gamma = 8.333 fs,\ f_0 = 0.3 pHz,\ \tau = 33.33 fs$$

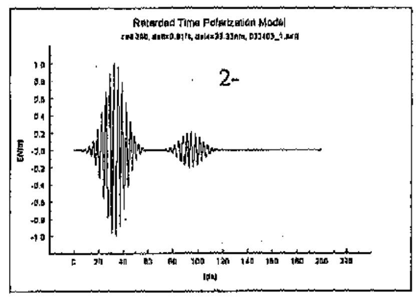
Field Propagation Checkout - I

Pulse propagates to right into a thin Si foil

1- Electric field at a fixed point in Si near left side. First incident pulse later reflection from right side.



2- Electric field at a fixed point in center of Si. First is incident pulse later reflection from right side.



Transit times and transmission/reflection coefficients agree with known values

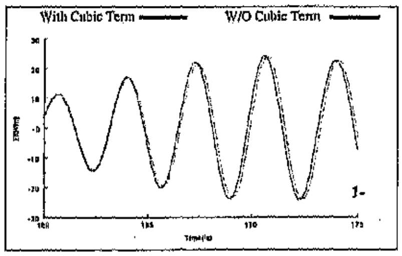
Field Propagation Checkout Results - II

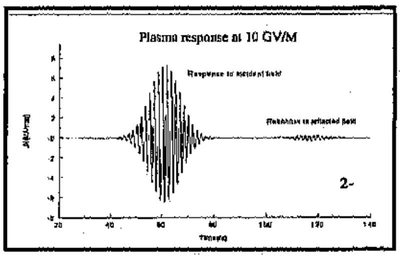
1- Kerr effect on speed in Si (20 GV/M)

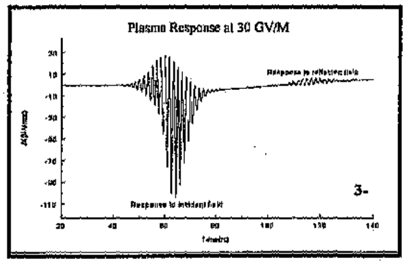
2- Induced current in air plasma at lower intensity

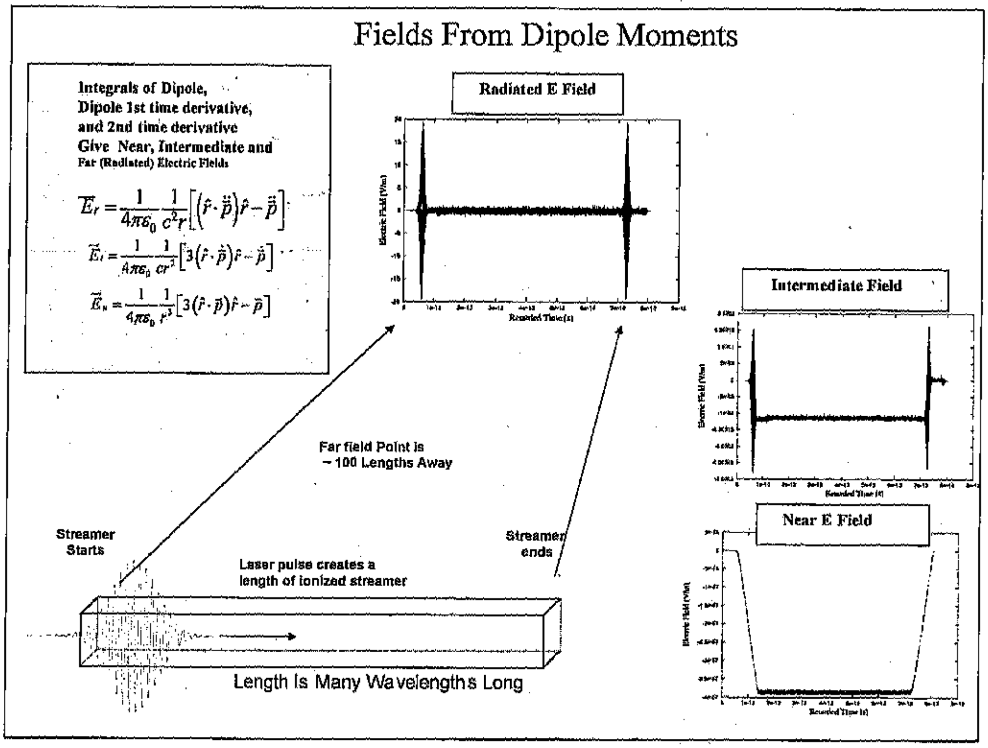
3- Induced current in air plasma at higher intensity

Showing non linear behavior





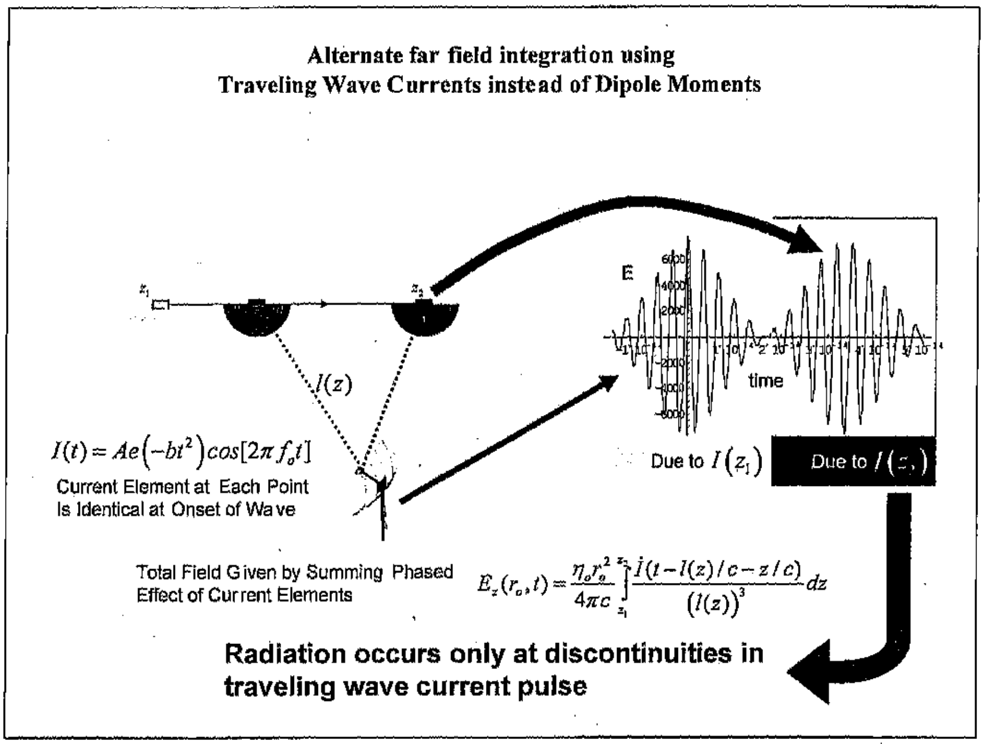




Comments on this Chart:

The question of whether RF radiation can be generated from a traveling Current pulse can be found by integratin over the moments of the dipole distribution, accounting for time retardation (coherence) .

The usual expansion of the fields into near intermediate and radiated components can be found.



An alternate derivation is to proceed from the propagating current distribution.

Standard expressions for the radiated field can be evaluated. This of course gives the same result as found from the dipole moment integration.

Conclusions

1- First principles analysis indicates no radiated field from a uniformly propagating ionization streamer
2- The predicted ionization densities/collision frequencies would abruptly damp out any oscillations in the ionization
3- Maxwell simulations showed both optical frequencies and a low frequency component. The low frequency is not low enough to explain reported sub THz radiation.
4- Observation show numerous streamers in one laser beam.
NLSE simulations indicate the formation and extinction of multiple ionization Streamers. These non steady state features have not been analyzed here
5- Our simulation do not indicate any sub THz radiation.
6-Mechanisms to explain reported observations are not well understood.

Test Case, Dielectric Model (Continued)

Analytic Estimate for the transverse and longitudinal Current Densities

transverse	*longitudinal*
$z(polarization) \cong 7.02\times10^{-12}\,m$	$x(polarization) \cong 1.55\times10^{-16}\,m$
$v_z(polization) \cong 1.32\times10^{4}\,m/s$	$v_x(polarization) \cong 5.48\times10^{-1}\,m/s$
$J_z \cong 5.61\times10^{10}\,A/m^2$	$J_x \cong 2.48\times10^{6}\,A/m^2$

Numerical results for the transverse and longitudinal current densities

transverse	*longitudinal*
$z(polarization) \cong 1.21\times10^{-11}\,m$	$x(polarization) \cong 4.65\times10^{-16}\,m$
$v_z(polarization) \cong 2.25\times10^{4}\,m/s$	$v_x(polarization) \cong 1.55\times10^{0}\,m/s$
$J_z \cong 9.40\times10^{10}\,A/m^2$	$J_x \cong 7.24\times10^{6}\,A/m^2$

The analytic and numerical results are in reasonable agreement

Analytical and numerical results are shown on this slide.

As can be seen the analytical and numerical results are in good agreement. comparison with the previous slide